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Research article

Optimal supplementary frequency controller design using the wind farm frequency model and controller parameters stability region

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ABSTRACT

In most of the existing studies, the frequency response in the variable speed wind turbines (VSWTs) is simply realized by changing the torque set-point via appropriate inputs such as frequency deviations signal. However, effective dynamics and systematic process design have not been comprehensively discussed yet. Accordingly, this paper proposes a proportional-derivative frequency controller and investigates its performance in a wind farm consisting of several VSWTs. A band-pass filter is deployed before the proposed controller to avoid responding to either steady state frequency deviations or high rate of change of frequency. To design the controller, the frequency model of the wind farm is first characterized. The proposed controller is then designed based on the obtained open loop system. The stability region associated with the controller parameters is analytically determined by decomposing the closed-loop system's characteristic polynomial into the odd and even parts. The performance of the proposed controller is evaluated through extensive simulations in MATLAB/Simulink environment in a power system comprising a high penetration of VSWTs equipped with the proposed controller. Finally, based on the obtained feasible area and appropriate objective function, the optimal values associated with the controller parameters are determined using the genetic algorithm (GA).

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1. Introduction

Renewable energy sources (RESs) have recently attracted more attention due to the environmental concerns, trends towards the energy market diversification, and high cost of fossil fuels [1,2]. Among different types of RESs, wind energy is the most economical option, which has experienced a fast technological advancement after the oil crisis in 1970s [3]. For instance, by the end of 2015, the total capacity of installed wind turbines has been approximately 430 GW, which represents a cumulative growth of 17% [4]. Wind turbine generators are considered as non-dispatchable resources due to the intermittent nature of the wind energy. Thus, integration of the wind turbine generators into the power system can significantly affect the reliability of power supply [5,6]. Some of the viable solutions to address this problem are using the power regulation [7,8] and operating reserve [9], scheduling the distributed generation units [10–12], using demand side management [13,14], deploying the energy storage systems [15], interconnecting to the neighbor areas [16,17], and integrating advanced controllers into the wind energy conversion system (WECS) structure [18–21].

During the recent years, variable speed wind turbines (VSWTs) have become the dominant type of WECSs. The VSWTs are interfaced to the main grid using the power electronic converters to absorb the maximum power from the wind energy [22,23]. These converters decouple the VSWTs from the grid. Therefore, no frequency response is provided by the VSWTs. In other words, the VSWTs typically cannot change their output power when a sudden power imbalance occurs in the network [24,25]. A viable solution is to employ a supplementary frequency controller, which enables the VSWTs to control their output power in accordance with the power system requirements. The extra required power during the frequency support period can be extracted from the kinetic energy in the wind turbine blades. This leads to variations in the rotor speed as well as excursions in the converter's current, which should be compensated afterwards [26].

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Notice that the VSWT's frequency controller is a local controller which responds to the active power imbalances based on its deduction from the size of disturbance. From this point of view, it is the dual of droop control mechanism in the conventional units. Therefore, no communication infrastructure is required for the implementation of such a controller, and hence, it not necessary to perform time delay stability analysis or delay compensation algorithms [27–29] in this case.

There exists a rich body of literature related to the power system frequency response with the increasing penetration of wind generation and implementation of frequency controller in the VSWTs [30–32]. Some important factors affecting the inertial response are reviewed in Refs. [33–35]. The works in Refs. [36–38] proposed the frequency controller embedded in the rotor speed controller. This control loop causes the VSWTs to emulate the synchronous machine inertial behavior. In contrast to the hybrid operation strategies proposed in Refs. [39,40], this cost-effective solution helps the grid code requirements to be satisfied without any additional hardware [41]. The work in Ref. [42] showed that VSWTs' inertial response capability can be more impressive than the synchronous machines with the same inertia constant due to the wider acceptable range of speed variations in VSWTs. The authors in Ref. [43] analytically proved that the power system frequency response can be improved with the embedded inertial control loop. In Ref. [44], quantity estimation of the extractable kinetic energy after any active power imbalances was discussed. Several manufacturers such as GE [41] and Enercon [45] have recently included the frequency controller in their products.

This paper mainly focuses on developing the model for a wind farm participating in the frequency regulation task. A proportional-derivative (PD) frequency controller is designed based on the obtained model. The performance of the proposed controller is evaluated and the optimal value associated with the controller parameters are determined. The main contributions of this paper are as follows:

- To design the controller, the VSWT's state space frequency model is developed using its pre-specified simple representation in the frequency studies. In particular, the obtained model includes the influences of the main torque controller, rotor intrinsic damping, and wind speed variations. The developed frequency model is then extended to the wind farm level. It is shown that the aggregated frequency response of the wind farm can be affected by the grid-wide penetration level index of the wind power. Contrary to the most of existing works which simply change the torque set-point via an appropriate signal, the basic power system frequency model (load-generation mismatch equation) is considered in the state space representation of the wind farm to activate the inertial response.
- A PD controller is suggested as the frequency support controller, which can directly change the rotor or stator quadrature voltage of VSWT (based on its type). This type of controller with frequency deviation input signal causes the VSWT to apply two important active power mismatch indices, i.e., the frequency deviations and the rate of change of frequency (ROCOF), in order to obtain the intended frequency response. To confine the controller's reaction to the middle frequency range components, a band-pass filter is also deployed before the controller. The stability region associated with the controller's parameters is then analytically computed by decomposing the overall closed loop system's characteristic polynomial into the odd and even parts and simultaneous equating both parts to zero. This region characterizes the feasible area for the controller's parameters.
- Different case studies are considered to evaluate the performance of the proposed controller and several deductions are derived from the time domain simulations and eigenvalue analyses. Improvement in the frequency behavior is justified in comparison with the cases without frequency support by the wind farm. It is proved that at the expense of losing the perfect torque regulation, damping of the mode associated with the frequency will increase with the embedded frequency controller in the VSWTs. The inconsistency in the operation of the main torque controller and the auxiliary frequency controller is emphasized. The impacts of the penetration level and intermittent wind speed on the power system frequency response are investigated. It is shown that at a higher penetration level, the frequency behavior improves at first and then deteriorates. The improvement is due to a higher output power of the VSWTs during the frequency support period. The lack of further improvement in the frequency response is due to the subsequent transient recovery period after a certain penetration level. As a comparative study, the superiority of the proposed controller with respect to other frequency controllers is also verified. Moreover, the impacts of nonlinear constraints associated with different parameters are notified. Finally, the genetic algorithm (GA) is used to determine the optimal parameters of the controller and band-pass filter.

The rest of the paper is organized as follows. Section 2 introduces the state space model required for the controller design. Section 3 is devoted to the synthesis of the proposed frequency controller and its stability region. In Section 4, the VSWTs with the proposed controller are embedded in the power system model and the performance of controller is evaluated under different operating conditions. Furthermore, the optimal parameters of the controller and filter are computed. Section 5 concludes the paper.

2. Wind Farm's frequency model

Participation of VSWTs in the frequency regulation is necessary in a power system with high penetration level of wind energy [1]. Application of power converters in the structure of VSWTs causes them not to be equipped with an intrinsic inertial response. However, such a response can be emulated by modifying their conventional control system or adding a supplementary frequency controller. Notice that the VSWTs are generally divided into the doubly-fed induction generator (DFIG) type and the full power converter (FPC) type. It can be shown that the active power can be adjusted through changing the q-component of rotor voltage in the DFIG type and changing the q-component of stator voltage in the FPC type [46,47]. In the literature, it is mentioned that the detailed models are not suitable for the frequency studies. In this trend, the following state space model is given to investigate the frequency behavior of VSWTs [48]:

$$s\Delta i_q = -\left(\frac{1}{T_1}\right)\Delta i_q + \left(\frac{X_1}{T_1}\right)\Delta v_q, \tag{1a}$$

$$s\Delta\omega = -\left(\frac{1}{2H}\right)\Delta T_e + \left(\frac{1}{2H}\right)\Delta T_m, \tag{1b}$$

where s is a complex number frequency parameter in the Laplace transformation. The variables i_q, and v_q are the rotor's quadrature current, rotor's quadrature voltage in the DFIG type and the stator's quadrature current, stator's quadrature voltage in the FPC type, respectively. Moreover, ω, T_e and T_m are rotational speed, electromagnetic torque and aerodynamic torque, respectively. The parameter H denotes the wind turbine's inertia. Furthermore, the parameters X_1, and T_1 are described in Table 1 for the DFIG and FPC types. In this table, the parameters L_m, L_{rr} and L_{ss} are the magnetizing inductance, rotor self-inductance, and stator self-inductance, respectively. Parameters R_r and R_s are the rotor and stator resistances, respectively. The parameter L_0 in Table 1 can be calculated as $L_0 = L_{rr} - \frac{L_m^2}{L_{ss}}$.

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